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HIGH-RESOLUTION EARTHQUAKE RELOCATION IN CASCADIA

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Abstract

In this 1-year project, we initiated application of the double-difference (DD, [*Waldhauser and Ellsworth*, 2000]) earthquake location algorithm to earthquakes in western Washington and in the Entiat/Chelan region of eastern Washington. The objective is to test our ability to refine the relative locations of clusters of earthquake, with the objective of improving our ability to associate earthquake locations with known or suspected crustal faults, and to relate fault slip to tectonic deformation. The ultimate objective is to improve our understanding of earthquake hazards in Cascadia. In this initial study, we have set up the data and computer resources for this investigation, and have carried out preliminary analysis of three clusters of earthquakes. In all three cases, the method has provided apparent increased resolution in the relative hypocenter locations, and these results suggest possible fault associations. In the case of the sequence near Entiat (Lake Chelan), our preliminary results in combination with recent determination of the event epicenter by [*Bakun et al.*, 2002] , suggest that a southwest dipping thrust fault could be the source of the 1872 M ~7 earthquake (the largest historic crustal earthquake in Washington). Analysis of aftershocks of the Bremerton magnitude 4.9 earthquake of June 1997 suggests the existence of a mid-crustal (14 km depth) sub-vertical fault rupture, with oblique slip north-side up and eastward, with possible but indirect relationship to the Seattle fault zone. A persistent sequence in the south Puget basin (south Kitsap peninsula) is more complex, but the double-difference locations resolve the sequence into two possibly parallel fault planes at mid-crustal depth that may be related to the Tacoma fault zone [*Thomas M. Brocher et al.*, 2004] .

Introduction

From SHIPS and related investigations, tremendous strides have been made in understanding the structure of the crust and upper mantle in the central Cascadia forearc region. Three papers have been recently published, based on the SHIPS experiments and earlier active source experiments plus earthquake data, providing detailed structure images and interpretation within the Puget Lowland [*U.S. ten Brink et al.*, 2002; *T. M. Brocher et al.*, 2001; *Van Wagoner et al.*, 2002] . Other geophysical and geological studies provide further information about the relationship of shallow structure, crustal faults and earthquakes particularly within western Washington and western Oregon [e.g., *Johnson et al.*, 1996; *R. J. Blakely et al.*, 1999; *R. J. Blakely et al.*, 2002; *R. E. Wells et al.*, 1998; *R. S. Ludwin et al.*, 1991; *Thomas M. Brocher et al.*, 2000] . Several additional investigations utilizing various aspects of the SHIPS data are in process of publication among the various collaborative groups participating in SHIPS.

It is difficult to directly associate earthquake activity in the Lowland region with known structural features. The structure of this region is complex, and surface mapping of faults is sparse. Some of this complexity is illustrated by Figure 1, from the paper by *Van Wagoner et al.*, [2002] . Much of the crustal earthquake activity in this region lies in the mid-crust, from 15 to 30 km depth, making it particularly important to have good 3-D structure information to connect surface structure with activity at depth. From the recent 3-D seismic structure studies, large seismic velocity variability is found in the crust of the Puget lowland, with velocity varying from 2 km/s or less in the shallower sedimentary basins, to over 7 km/s at moderate depths in the crust in rocks that may be of gabbroic composition. Large lateral variations in crustal velocity have a significant impact on conventional earthquake location methods that utilize laterally homogeneous crustal models. This structural complexity may contribute in part to the apparent complexity of hypocenter patterns in this region.

Figure 2 shows the 2003 PNSN station configuration, and Figure 3 is an epicenter map of nearly 50,000 earthquakes through 2001, selected from the PNSN catalog. Comparison of Figures 1 and 3 illustrate some of the difficulties in relating earthquake distribution patterns with surface geologic structure.

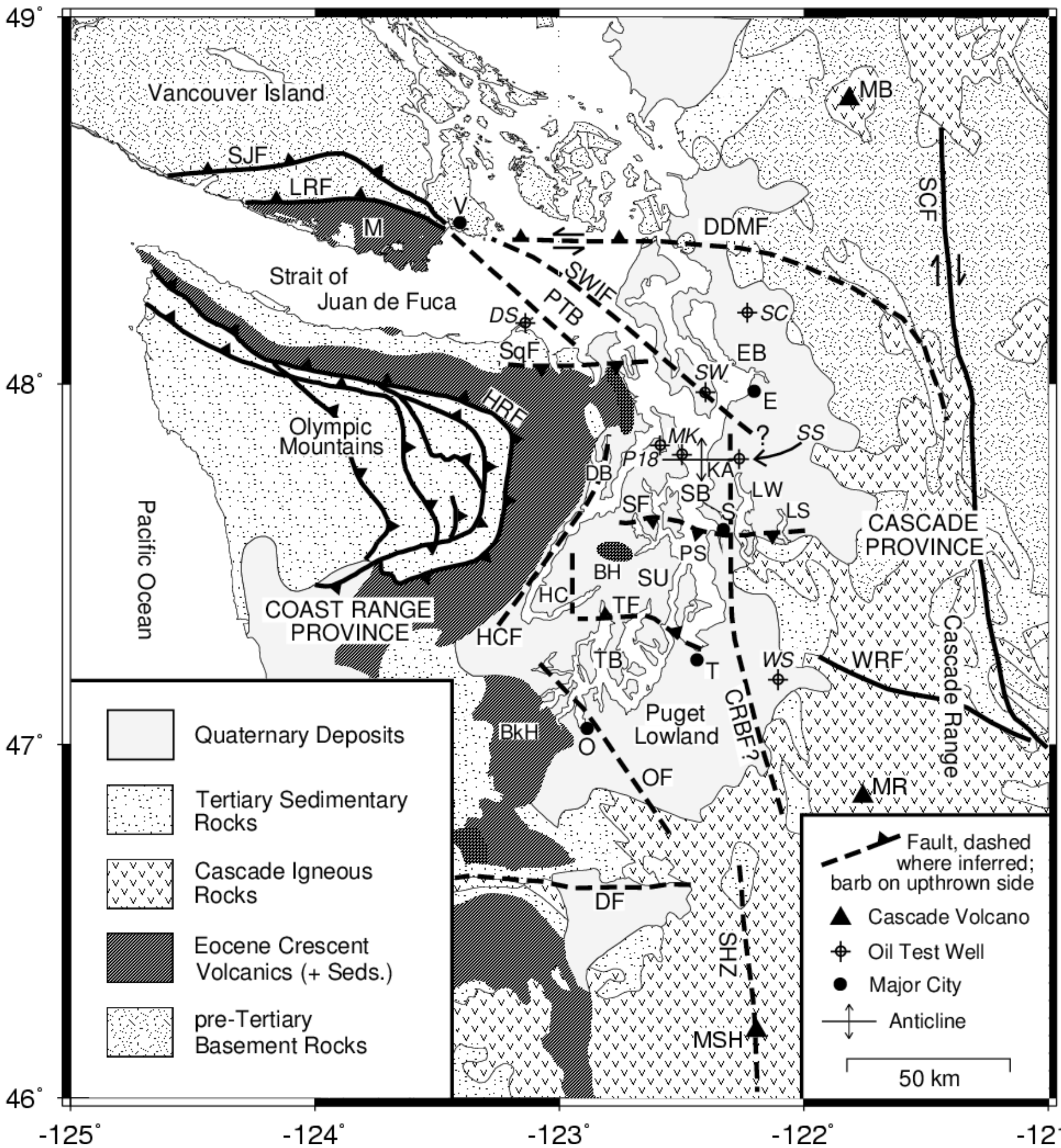

Figure 1. Generalized geological map of the central Cascadia forearc region. Map is adapted from paper by Van Wagoner et al. [, 2002 #154] based on sources cited in text. Selected symbols are: SF = Seattle fault; SWIF = South Whidbey Island fault; SU = Seattle uplift; DDMF = Darrington-Devils Mt. fault; TF = Tacoma fault; SB = Seattle basin; OF = Olympia fault. Comparison of this figure with the epicenter map of Figure 3 shows the complexity of fault-epicenter correlation in this region.

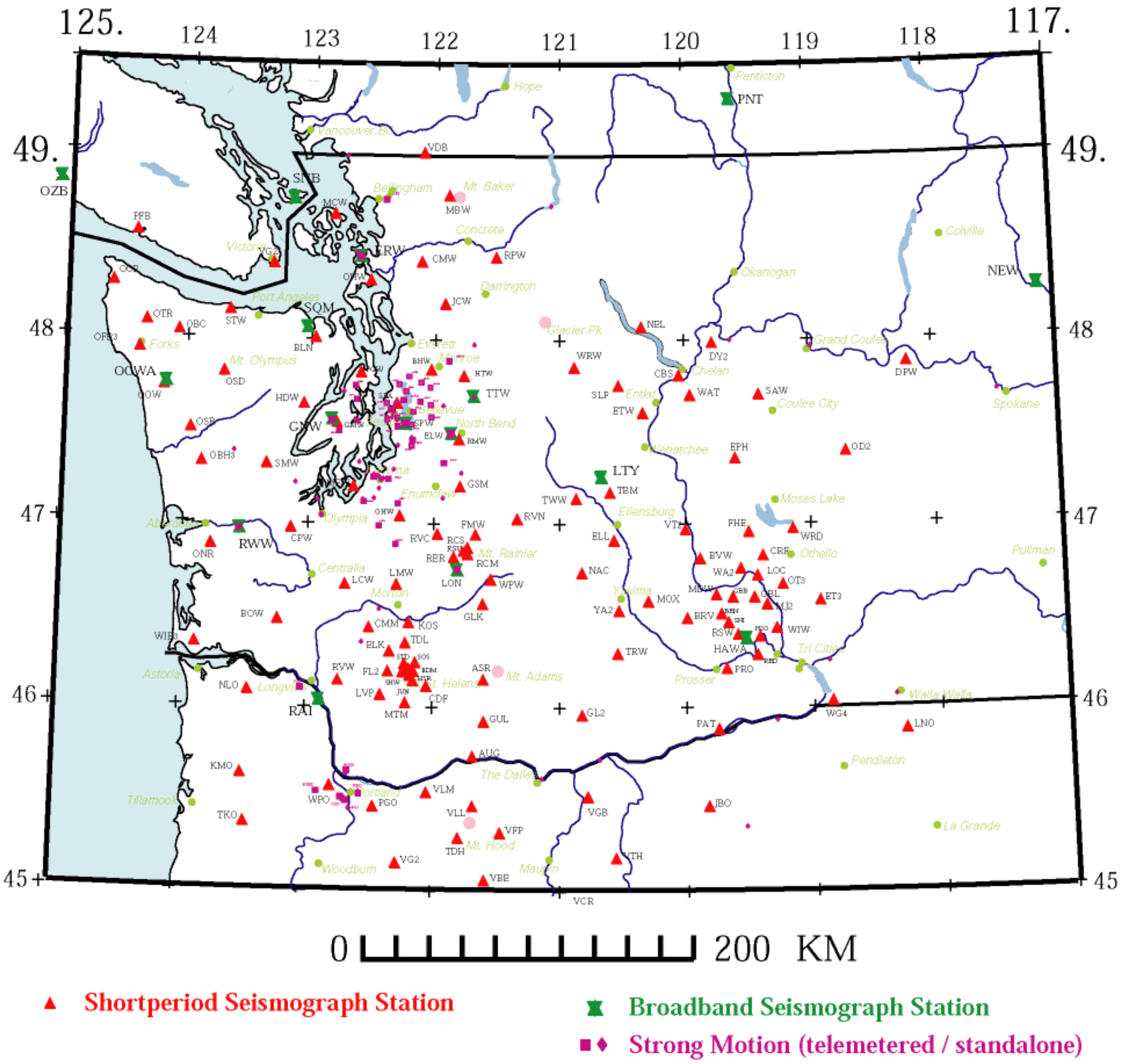

Figure 2. Map of the northern portion of the Pacific Northwest Seismograph Network (PNSN). Dark triangles are basic short-period backbone stations, and squares/diamonds are newer strong motion stations installed mainly in the central Puget basin region. Hour glass shaped symbols are newer broadband telemetered stations.

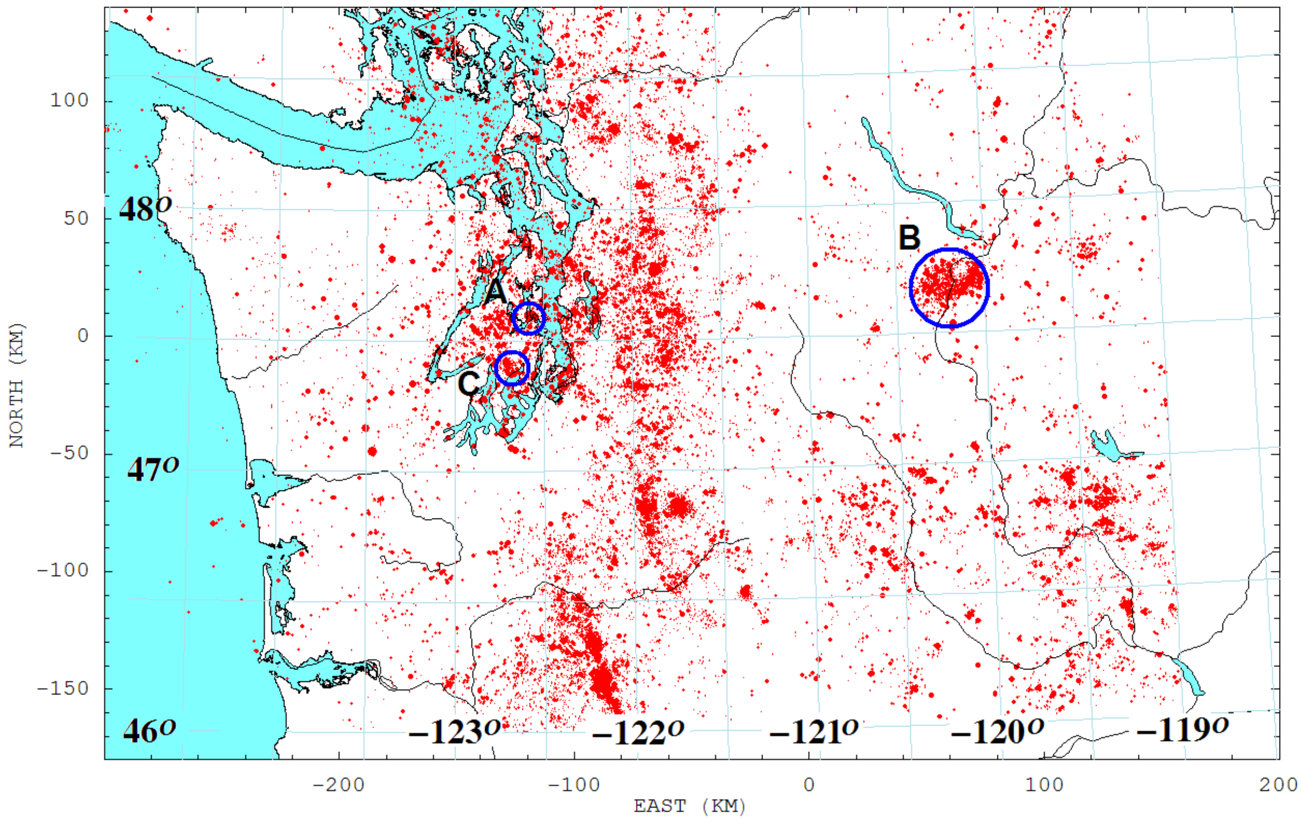

Figure 3. Epicenter map for earthquakes selected from the PNSN preliminary location catalog. The data set includes approximately 50,000 instrumentally located earthquakes from 1969 through 2001. Magnitude symbol scaling is used but is not readily visible at this scale. The Bremerton sequence of 1997 is indicated by circle A, the Entiat-Chelan sequence is circle B, and the south Kitsap Peninsula sequence is indicated by circle D.

Research Results

The “double-difference” method allows the mixture of cross-correlation generated time differences at stations and conventional catalog data. Through appropriate grouping of observations according to clustering criteria, and weighting inter-cluster observations, *Waldhauser and Ellsworth's* method (implemented in the computer program “hypoDD”) works successfully on more widely dispersed hypocenters than previous methods (e.g., [*Got et al.*, 1994]). *Wolfe [*2002] further explores the theoretical underpinnings of double-difference relocation, investigating in detail the fundamental strengths and limitations of the methods. She notes that a fundamental difference between Waldhauser and Ellsworth’s method and earlier methods such as that of Got et al. is the potential for the Waldhauser and Ellsworth method to resolve the hypocentroid (effectively mean location of a group of earthquakes) due to the use of partial derivatives evaluated at variable source locations when the coefficient matrix is formed.

The use of hypoDD relocation is demonstrated in three examples from the PNSN data set. We expect this new methodology to improve relative locations of clusters of earthquakes, allowing us to identify the orientation of faulting and associate fault orientations with focal mechanisms and tectonic models. In this initial work with hypoDD, we utilize only catalog time picks.

Bremerton Sequence

The Bremerton M 4.9 earthquake of June 1997 and its aftershocks (cluster A of Figure 3) provide an example of the application of double difference relocation to a small earthquake cluster. The Bremerton earthquake is one of the larger crustal earthquakes recorded by the PNSN. It is also of interest because it is in the general vicinity of the western part of the Seattle fault zone (SFZ). Although its relationship to the SFZ is not entirely clear, it may have important tectonic implications for the SFZ. *Blakely et al. [*2002] discuss this earthquake in relationship to their inferred fault structure for the Seattle fault, and conclude that either the Bremerton sequence is directly related to the observed surface displacements on a high angle fault, or that it reflects slip on a nearly horizontal plane near the base of the Seattle basin.

Initial routine network locations placed the mainshock of the Bremerton earthquake at a depth of 7.7 km with aftershocks distributed over a vertical depth range from about 11 km to the surface. Subsequent reanalysis and relocation of the sequence placed the mainshock at a depth of about 13-14 km, but the aftershocks were still distributed over a vertical range from 13 km to the surface using conventional network location procedures. Focal mechanisms for the mainshock and several aftershocks were constructed, with one possible slip surface a nearly vertical fault plane parallel to the regional trend of the SFZ (as defined by gravity measurements and tomography studies; the auxiliary plane was sub-horizontal). The initial relocation studies revealed that the depth control for this mainshock-aftershock sequence was actually quite poor using conventional location procedures, in spite of the fact that the sequence occurred near the center of the regional PNSN network. Based on the conventional network locations, the large vertical distribution of aftershocks for the Bremerton sequence is too great to reflect occurrence on or near the mainshock slip surface.

As a test, we applied the double-difference algorithm to a set of 11 well-recorded earthquakes in the 1997 Bremerton sequence (using the program hypoDD). The 11 events comprise the mainshock and 10 aftershocks, with magnitudes ranging from 1.9 to 4.9. The events were all relocated with hypoDD using the standard central Puget basin 1-D velocity model. Whereas the routine network locations placed most of the aftershocks at depths less than two kilometers, with only 4 events deeper than 2 km, in the double-difference results all of the aftershocks “collapsed” into a tight circular cluster about 1.5 km in diameter at a depth of about 14.5 km. The plane of this cluster strikes NW and the cluster defines a nearly vertical plane in space that corresponds well with to orientation of the high-angle plane of the mainshock first-motion focal mechanism. This agreement allows us to assert with some confidence that the rupture plane is likely to be the nearly vertical plane: oblique slip with the northeast side block moving upward and eastward relative to the southwest side block.

Both routine network and double-difference solutions place the mainshock about 1 km SW of the map-view aftershock lineation. The reason for this displacement remains unclear. The offset is not the result of a single station anomaly – we investigated that possibility in our preliminary analysis. The aftershocks may occur on a subsidiary fault that was activated by the mainshock. Another possibility is that the difference in signal strength between the mainshock and the aftershocks, as a result of their size difference, resulted in different phases (different arrival "paths") being picked as first arrivals between the main and aftershocks. For example lateral refractions associated with the SFZ may be observed in the mainshock signals, but have amplitudes too low to be observed in the smaller amplitude aftershocks signals. The observed strong lateral variation in velocity from the Seattle basin southward across the Seattle fault zone could contribute to such effects. Further careful study may reveal the nature of this location difference.

Moving the Bremerton mainshock hypocenter from 8 km depth to 14 km depth places it within rocks of the Crescent formation, well below the sediments of the Seattle basin and consistent with regional background seismicity which is found to occur dominantly within the Crescent. The north-side-up character of the Bremerton earthquake, even at a depth of 14 km, suggests that fault displacement resulting from repeated earthquakes might ultimately reach the surface in the vicinity of the SFZ [*Blakely et al.*, 2002] .

Entiat-Chelan Sequence

The Entiat-Chelan region of eastern Washington, near the boundary between crystalline rocks of the north Cascades and the basalt flows of the Columbia Plateau, is a seismically active region on the eastern flank of the Cascade Range. This region is of particular interest because it is a likely source zone of the December 1872 M ~7 earthquake, widely regarded as the largest crustal earthquake in the historic record for Washington. *Bakun et al. [*2002] recently reanalyzed the felt reports for this earthquake, and concluded that the 1872 earthquake was a shallow (crustal) event, and that the epicenter coincides almost exactly with the hypocentroid (mean position) of the contemporary instrumental hypocenters in the region.

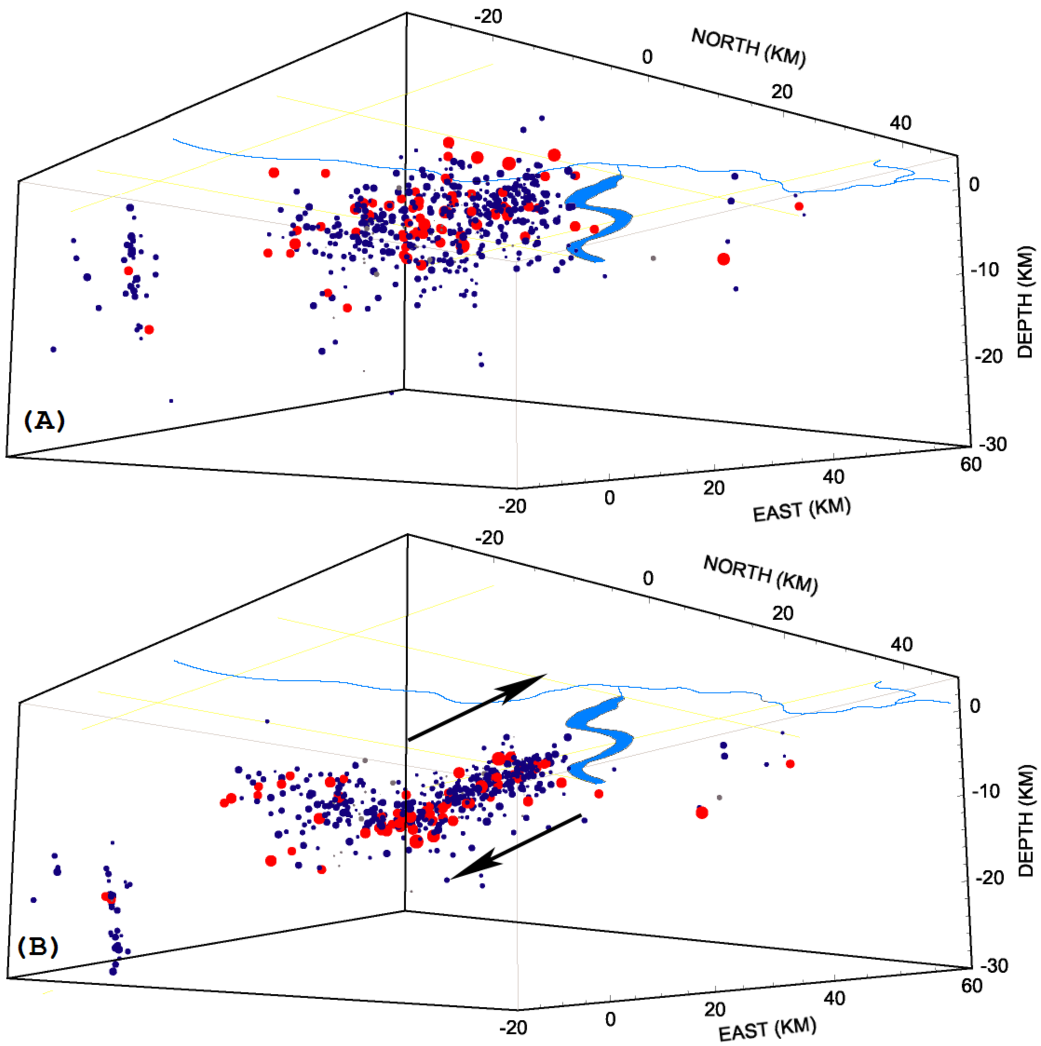

Figure 4. Identical 3-D views of the 577 event distribution for hypoDD relocated earthquakes: (A) initial locations using conventional (Geiger's method) locations, and (B) relocations using hypoDD. Size scaling is used for these plots, with linear scaling over the magnitude range from 0 to 3.5 . The "underside" of Lake Chelan is the sinuous feature on the upper surface of each plot. For plot (B) the full distribution is a sub circular disk viewed from the side. The arrows in (B) show the sense of motion indicated by focal mechanism analysis.

To see if any evidence of the fault plane of the 1872 event might be identified in the contemporary hypocenter distribution, we applied the double difference relocation technique to this sequence. We initially selected a group of 1198 earthquakes ranging in magnitude from 0 to 3.5, and in depth from the surface to about 15 km (a few outliers were at greater depth). The time window was from 1980 through 2001, and all quality levels were included in the initial selection. Only hand picked first arrival data in the PNSN phase catalog were used in this initial study.

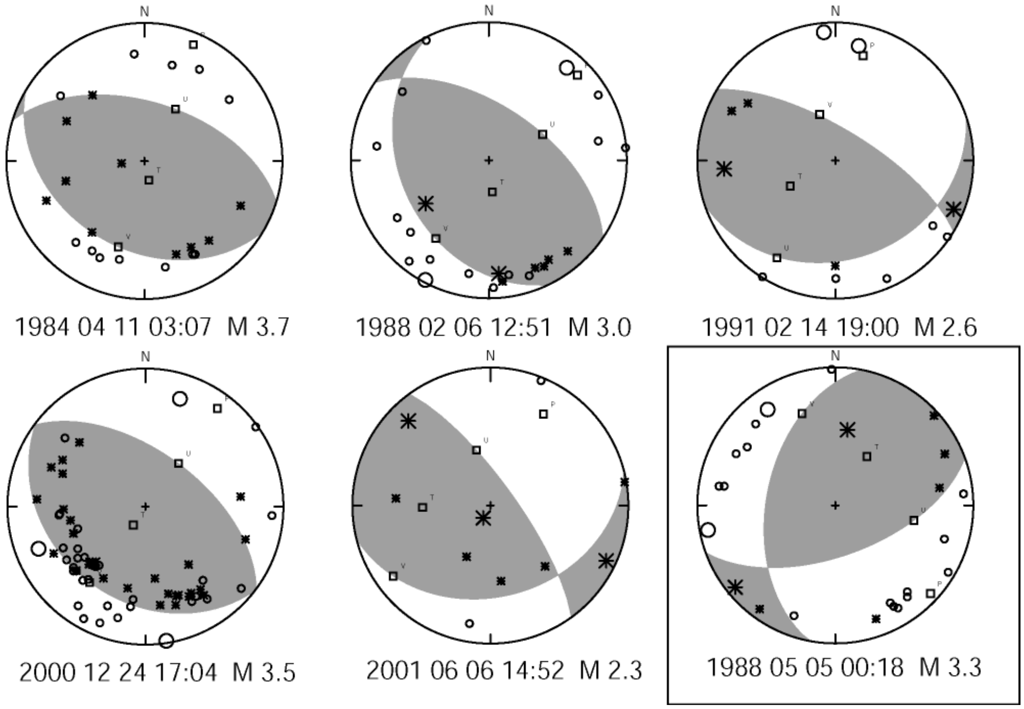

Figure 5. Focal mechanisms of 6 events within the relocated Entiat-Chelan sequence. Dates and magnitudes are indicated below each plot. These are lower hemisphere equal area plots, with compressional quadrants shaded. Symbols are: (*) for compressional observations and (0) for dilatational observations. Large symbols have takeoff angles in the upper focal hemisphere, and small symbols have takeoff angles in the lower focal hemisphere. Further work in refining the crustal velocity structure in this region may significantly improve our ability to determine focal mechanisms.

After relocation using hypoDD, the number of events successfully relocated was 577. Many events were deleted from the relocation due to insufficient numbers of picks and insufficient cluster density. However we observed a dramatic change in the hypocenter distribution from the initial conventional locations to the double difference relocations. This difference is illustrated in Figure 4 which shows the same 577 hypocenters in a 3-D view from the same viewing position: (A) the conventional locations and (B) the hypoDD relocated positions. The view point was chosen to optimally “flatten” the hypocenter distribution in the hypoDD results. The original locations produced a featureless cloud of hypocenters with no discernable structure. However the hypoDD results show a clear sub-circular planar hypocenter distribution dipping to the southwest at an angle estimated to be 15-20° with depths typically from 5 to 15 km. Although there is no clearly mapped surface expression of a fault or other features that might correspond to the thrust plane (see e.g., *Bakun et al.* [2002]) it is interesting that the projection of this plane to the surface roughly coincides with the average (linear) position of Lake Chelan. However, it is important to note from the hypocentral depths that the conjecture by *Bakun et al.* that the 1872 event may have occurred on a blind thrust is consistent with our analysis.

Since this hypocenter distribution suggests a possible thrust plane, we examined focal mechanisms of 6 events that had reasonably well distributed observations. The first arrival mechanisms for these events are shown in Figure 5. To obtain the mechanisms we approximated the local velocity structure by a linear velocity function, recognizing that more work needs to be done to refine the local velocity structure. Five out of the 6 events have mechanisms that are closely consistent with low angle thrust planes dipping to the southwest or south. The P axes for these mechanisms are typically NNE, generally consistent with the sense of compression observed in western Washington, and elsewhere in the Columbia basin. The arrows of Figure 4 (B) show the sense of motion indicated by the choice of the SW dipping fault planes. The sixth event, shown in the box, is consistent with thrust or reverse motion, but with the P axis oriented approximately 90° to the dominant solutions.

Although more detailed analysis should be undertaken to confirm these preliminary results, we suspect that we may be observing activity associated with the structure that gave rise to the 1872 earthquake. The details of crustal structure in this region are not well known. However, based on the located event depths, it is reasonable to believe that most if not all of the earthquakes in the Entiat-Chelan cluster occur in the crystalline basement rocks of the N. Cascades. As reviewed in detail by *Bakun et al*., there are no good known candidates for surface mapped faults in the region that could provide surface control for thrust faulting. The Entiat fault, the largest fault in the area (about 20 km SW of the earthquake cluster), appears to be a strike slip fault that has been inactive since the Eocene. The general sense of compression (NE-SW) expressed for example in the Yakima fold belt south of Entiat, is definitely consistent with the P axis orientation of the dominant focal mechanisms. Thus, there is reason to believe that both the earthquakes and surface deformation are reflecting regional tectonic stress conditions. Our results, in combination with the recent findings of *Bakun et al.* [2002], will contribute to improved understanding of the crustal earthquake hazard for this region.

South Kitsap Peninsula Sequence

Our final example of preliminary analysis is a persistent cluster of mid-crustal earthquakes occurring on the south Kitsap Peninsula in the Puget Lowland (Figure 3, cluster C). This cluster includes a M 4.6 earthquake in March 1978 reported by *Yelin and R. S. Crosson* [1982]. The rate of occurrence has been roughly constant over the time interval of our observations. Hypocenters in this cluster typically have depths in the 20-25 km range, so provide an excellent test case for mid-crustal earthquakes in the Puget Lowland region. Note from Figures 1 and 3 that this cluster occurs close to the apparent bend where the Tacoma fault changes its strike direction from NW to E. *Van Wagoner et al.* [2002] report focal mechanisms for events included in this cluster ranging from pure thrust to strike-slip, suggesting substantial structural and tectonic complexity for this region.

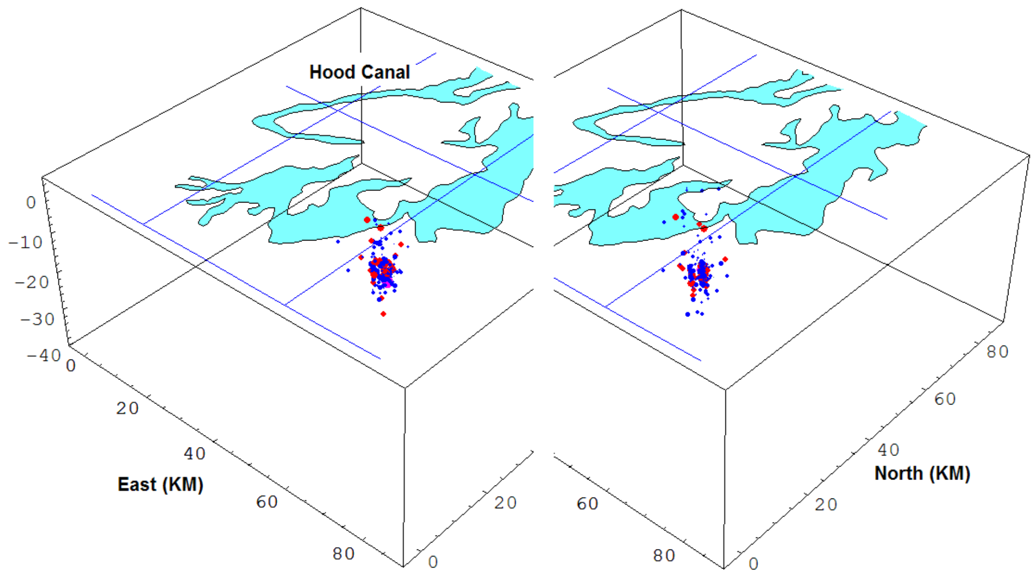

Figure 6. 3-D views from the SE of south Kitsap sequence hypocenters before relocation (left) and after relocation using hypoDD (right). The viewpoint was chosen to minimize the scatter of hypoDD relocations, revealing the possible existence of two parallel fault planes striking NW and dipping nearly vertically. The shaded regions represent the water areas of south Puget Sound.

A selection of 229 earthquakes was initially made from the PNSN phase catalog covering the time window 1970 through 2000. In this selection, lowest quality data ('D' quality factor) were rejected. HypoDD relocations were run on the selected data, resulting in 214 successfully relocated events. Although the initial cluster is tighter than the Entiat-Chelan cluster, the scatter of hypocenters was again reduced significantly. From Figure 6, comparing identical 3-D views from the SE – before-to-after relocation, it can be seen that two parallel and nearly vertical fault planes may be present. We caution that these results are preliminary and more thorough analysis is required to confirm and clarify this relationship. However, the NW oriented fault surface(s) are consistent with the strike of the east end of the Tacoma fault zone (TFZ) based on tomographic studies [*T. M. Brocher et al.*, 2001; *Van Wagoner et al.*, 2002]. It is interesting to note that the eastern section of the TFZ impinges on the crustal high velocity unit represented by the Blue Hills – Gold Mt. velocity high at the location of the south Kitsap cluster. This prominent velocity high may represent a crustal emplacement of basic intrusive (gabbros??), generally much stronger rocks than the rocks bounding the TFZ further east. Highly accurate relative hypocenter locations provide hope that the structural and tectonic cause of these earthquakes can be unraveled.

Publications, Reports and Abstracts relating to this project

(papers, abstracts, and meeting presentations)

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